Process-based Evaluation of Trade-Cumulus Feedback using observations

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Pan-GASS, Monterey, July 2022

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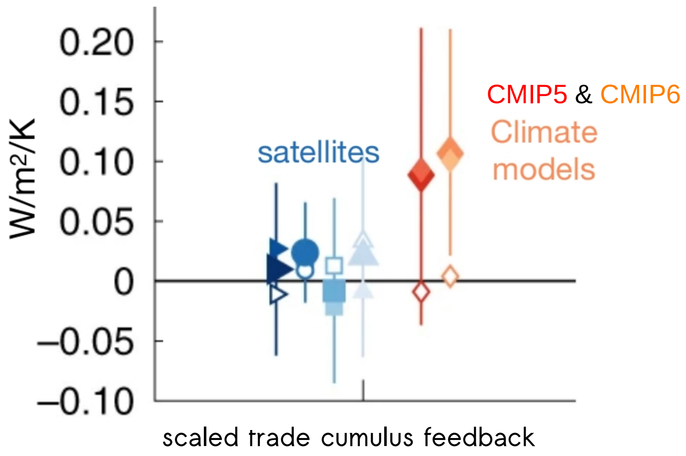
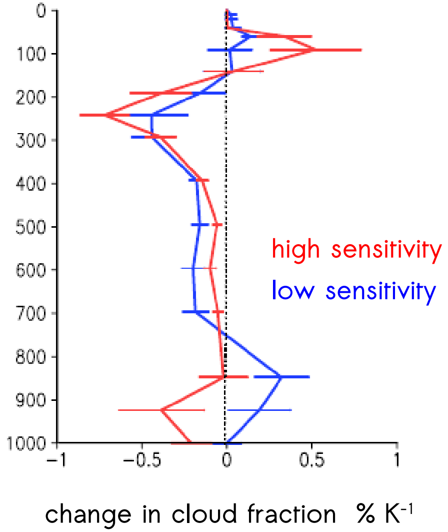
CFMIP
Cloud Feedback Model Intercomparison Project

- For nearly two decades, the trade-cumulus cloud feedback has remained a major source of uncertainty for climate sensitivity (e.g. CMIP3: Bony & Dufresne 2005, CMIP5 & CMIP6: Vial et al. 2013, Myers et al. 2021)
- Recent satellite studies suggest that many models exhibit a too strong cloud feedback in shallow cumulus regimes
- In climate models, trade cumulus feedbacks are governed by changes in cloud fraction near cloud base, with high climate-sensitivity models suggesting a dessication of the lower cloud layer when the lower-tropospheric mixing increases

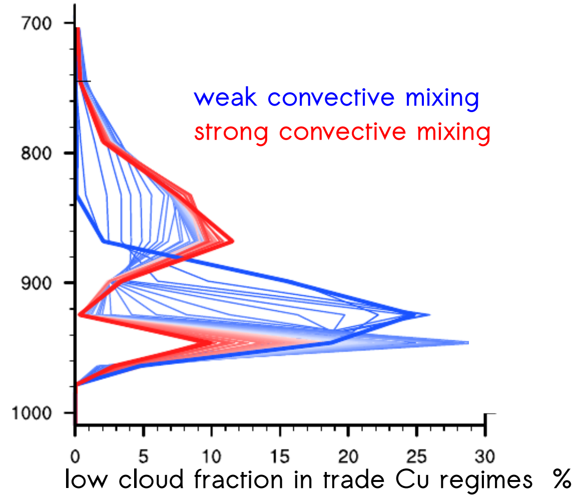


Myers et al., 2021

also Cesana and Del Genio 2021



Brient et al., 2016



Vial et al., 2016

also Rieck et al. 2012, Sherwood et al. 2014

In trade-cumulus regimes, what controls the cloud fraction near the cloud base level ?

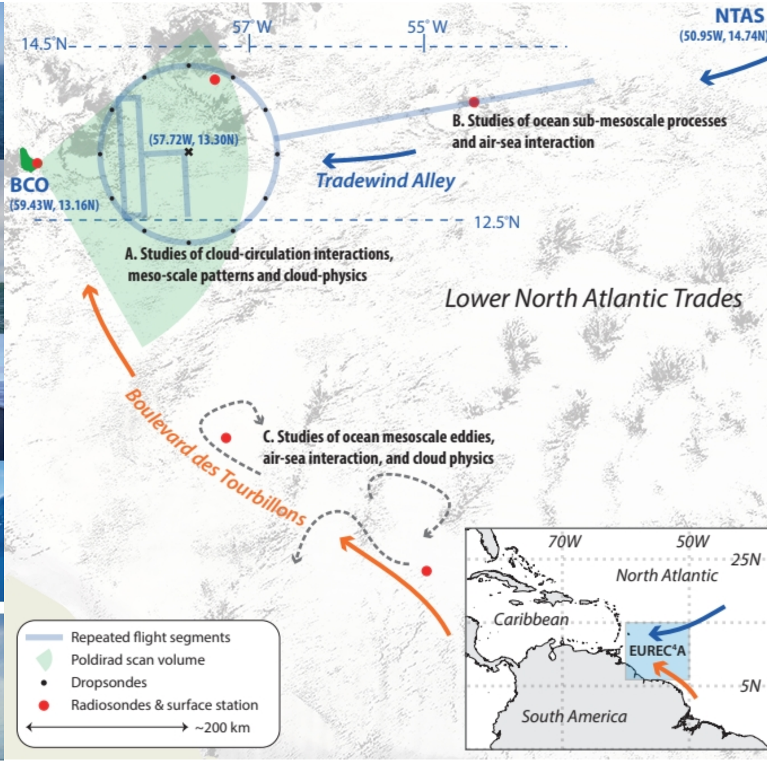
- Dynamical and thermodynamical controls
- Coupling between convection and humidity (e.g. through entrainment)

→ How much is C (cloud fraction near cloud base) controlled by M (mass flux) and RH (relative humidity) ?

→ Evidence for mixing-dessication mechanism ?

EUREC^{4}A (Elucidating the role of couplings between clouds, convection and climate) was designed to study the interplay between trade-wind clouds and their environment

It took place in Jan-Feb 2020 over the western tropical Atlantic near Barbados



Bony et al. (2017), Stevens et al. (2021)

EUREC^{4}A special issue : https://essd.copernicus.org/articles/special_issue1122.html

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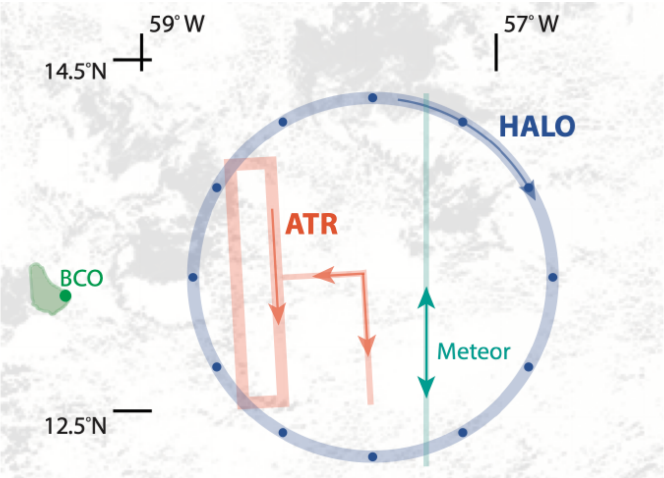
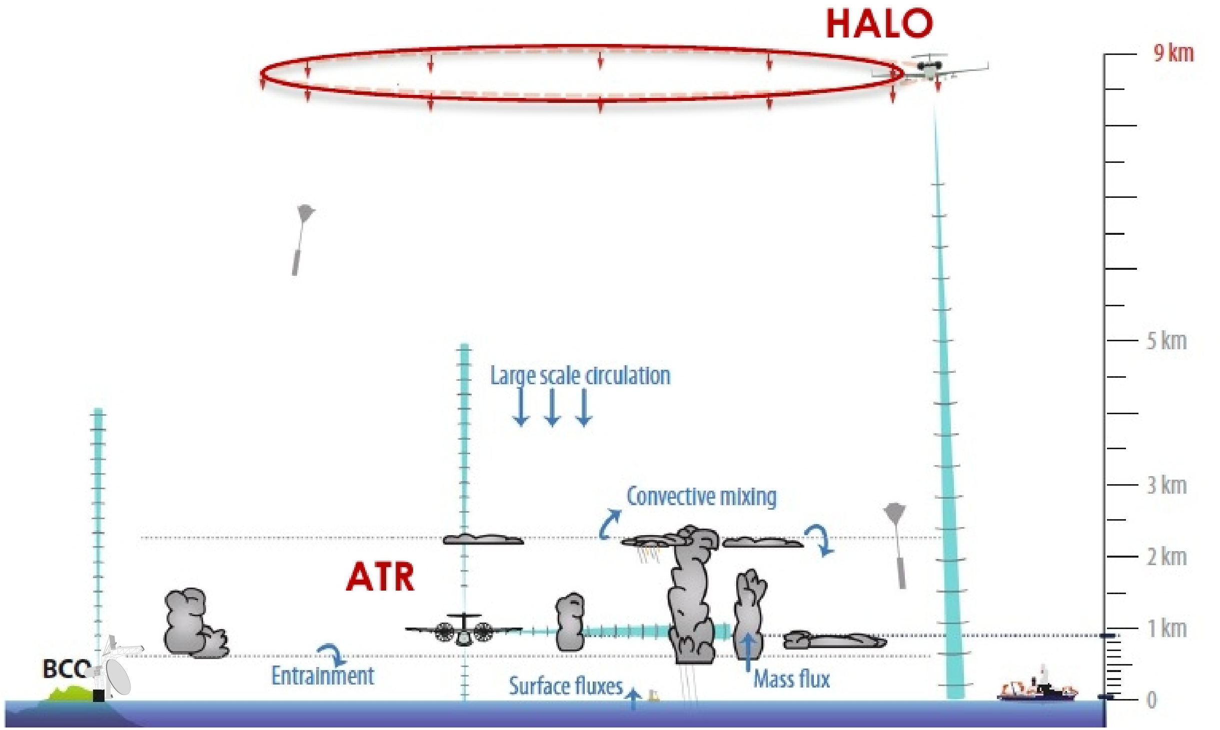
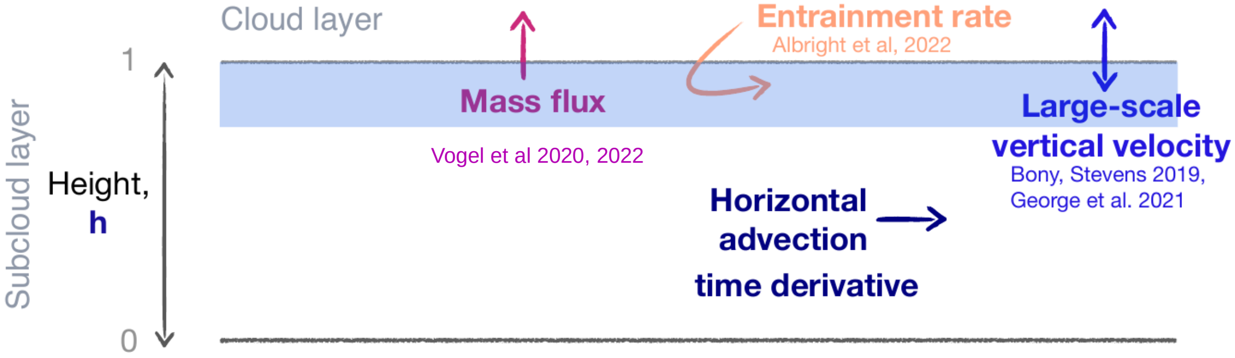




Bony et al. (2017), Stevens et al. (2021)

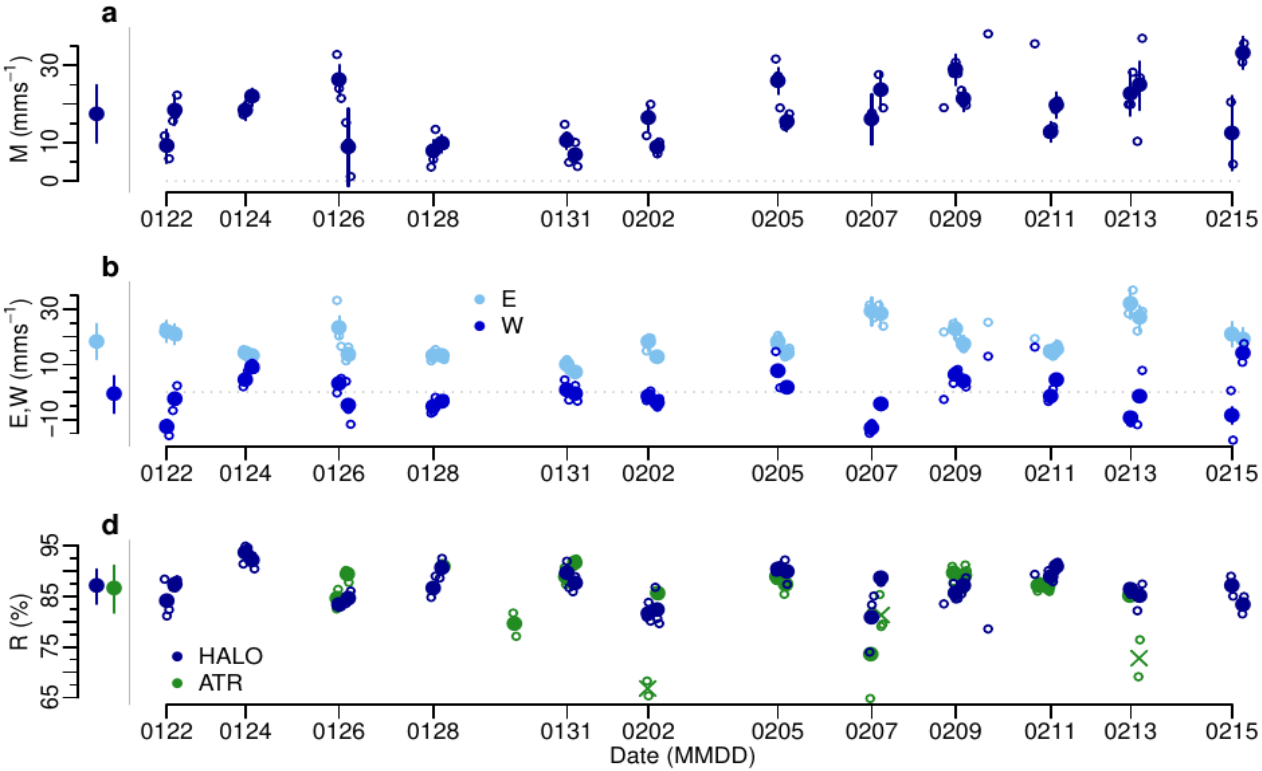
Dropsondes measurements

$$\frac{Dh}{dt} = E - M + W$$



Relative humidity (RH), Subcloud layer height (h), Entrainment (E), and mesoscale vertical velocity (W) near the cloud-base level inferred from dropsonde measurements (HALO)

Convective mass flux (M) estimated as a residual of the mass budget of the subcloud-layer (3-hourly timescale) :



$$M = E + W \quad \left(\frac{Dh}{dt} \text{ small}\right)$$

on monthly timescale : $M = E$

but on shorter timescales (3-hourly, daily) :

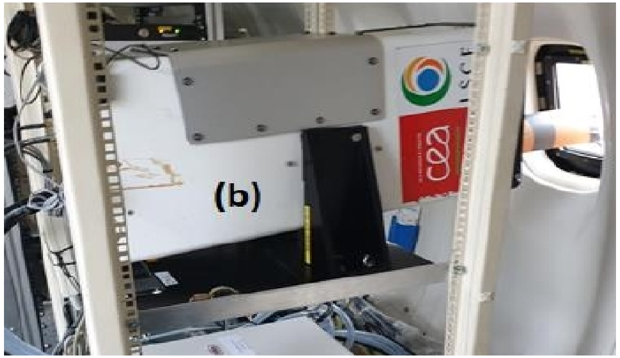
- E and W contribute equally to variability in M
- E and W have opposing effects on humidity

→ E and RH are anti-correlated
but M and RH uncorrelated

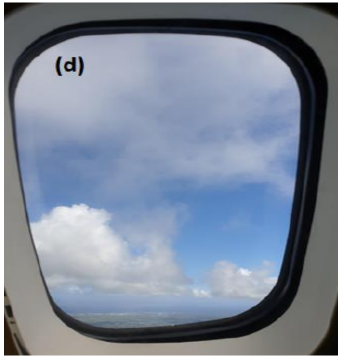
at odds with the mixing-dessication hypothesis

Vogel et al. (in revision)

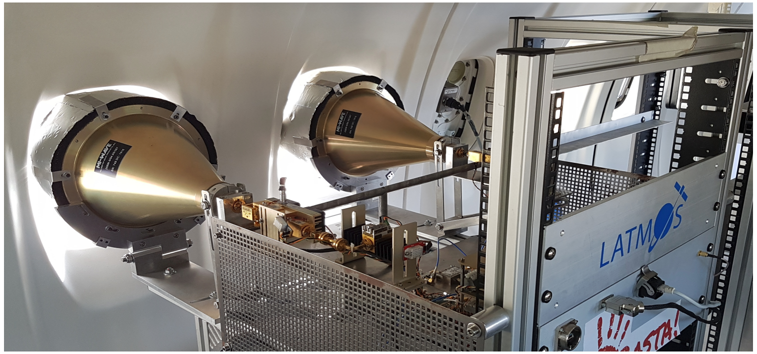
Horizontally-pointing lidar



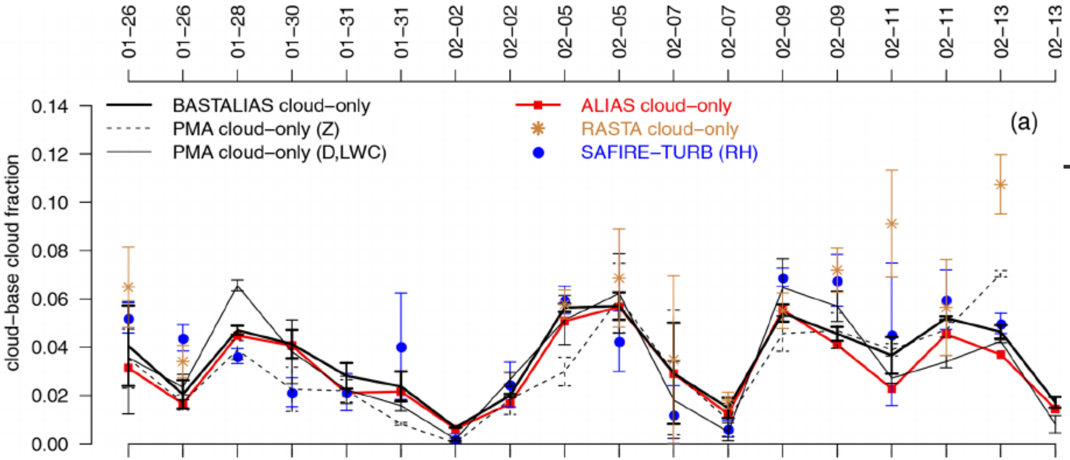
ALIAS 355 nm lidar (Chazette et al., 2020)



Horizontally-pointing radar



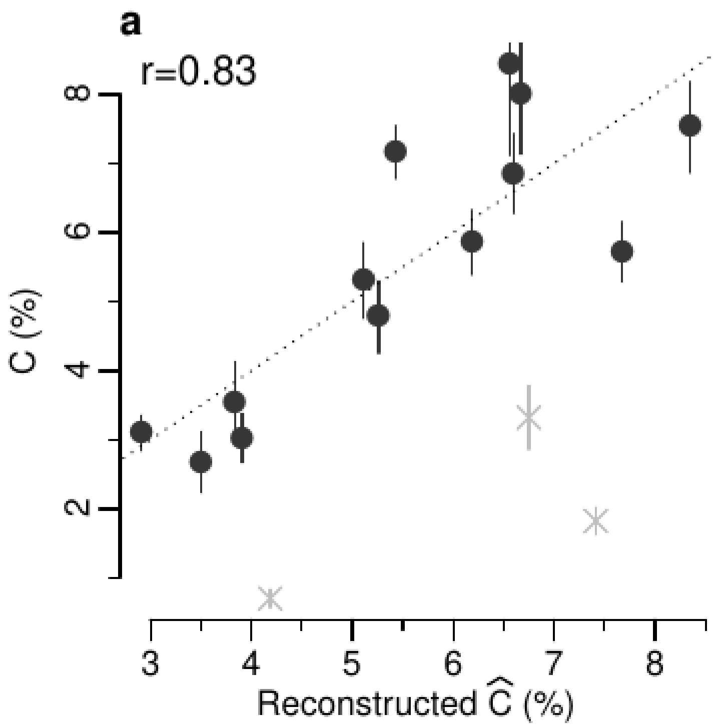
BASTA 94GHz Doppler cloud radar (Delanoë et al., 2016)

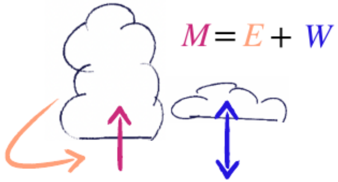


→ cloud fraction (C) measured near the cloud base level

Bony et al. (2022)

$$\hat{C} = a_{RH}\widetilde{RH} + a_M\widetilde{M} + a_0$$



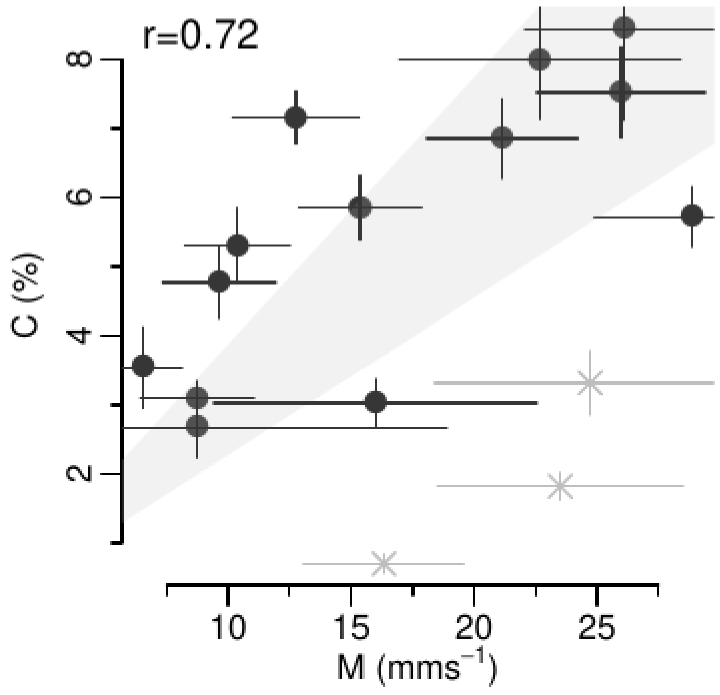


Thermodynamical control of clouds

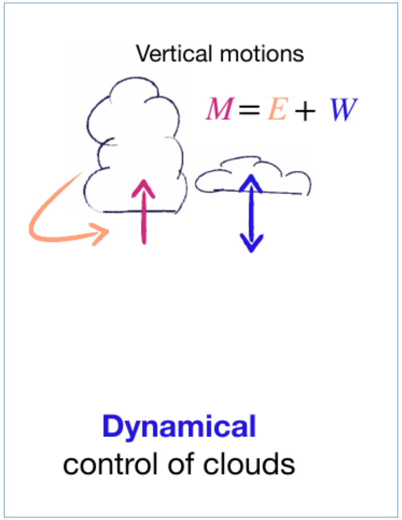
Dynamical control of clouds

Vogel et al. (in revision)

Dynamical control of clouds



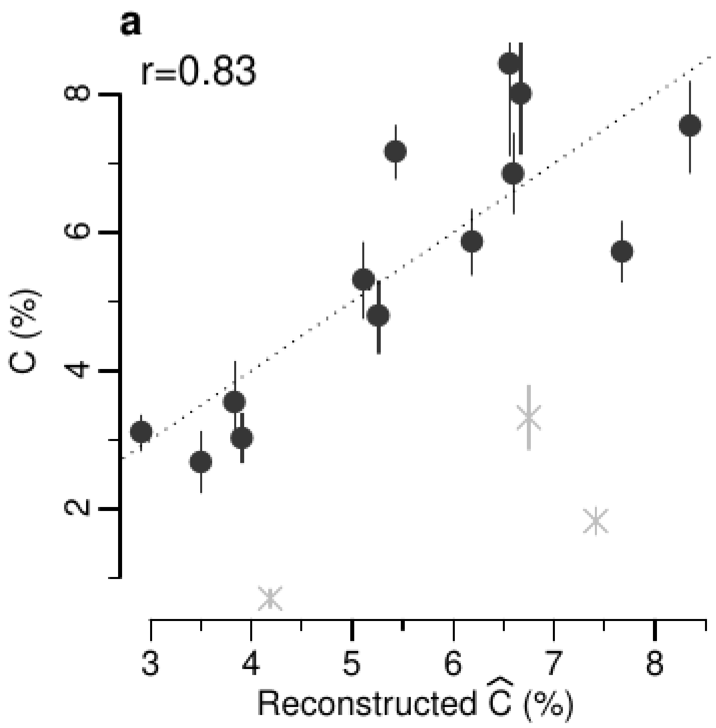
Because mesoscale motions and entrainment contribute equally to variability in mixing, but have opposing effects on humidity, mixing does not desiccate clouds.



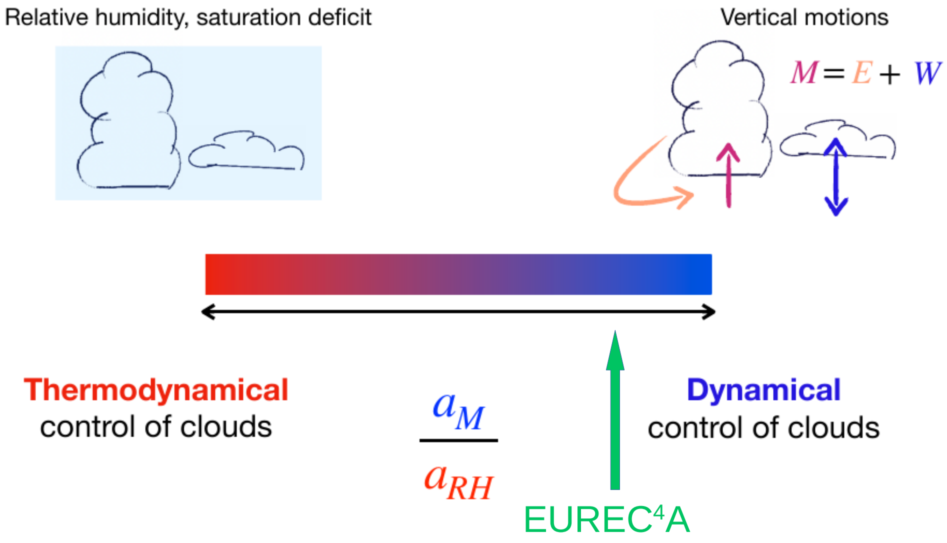
Vogel et al. (in revision)

Thermodynamical and dynamical controls of the cloud-base cloud fraction

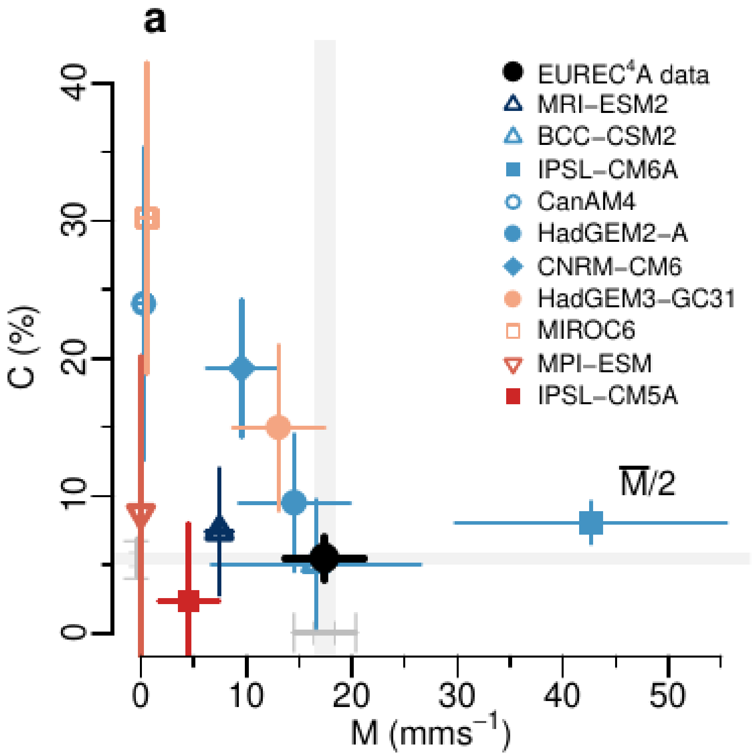
$$\hat{C} = a_{RH}\widetilde{RH} + a_M\widetilde{M} + a_0$$



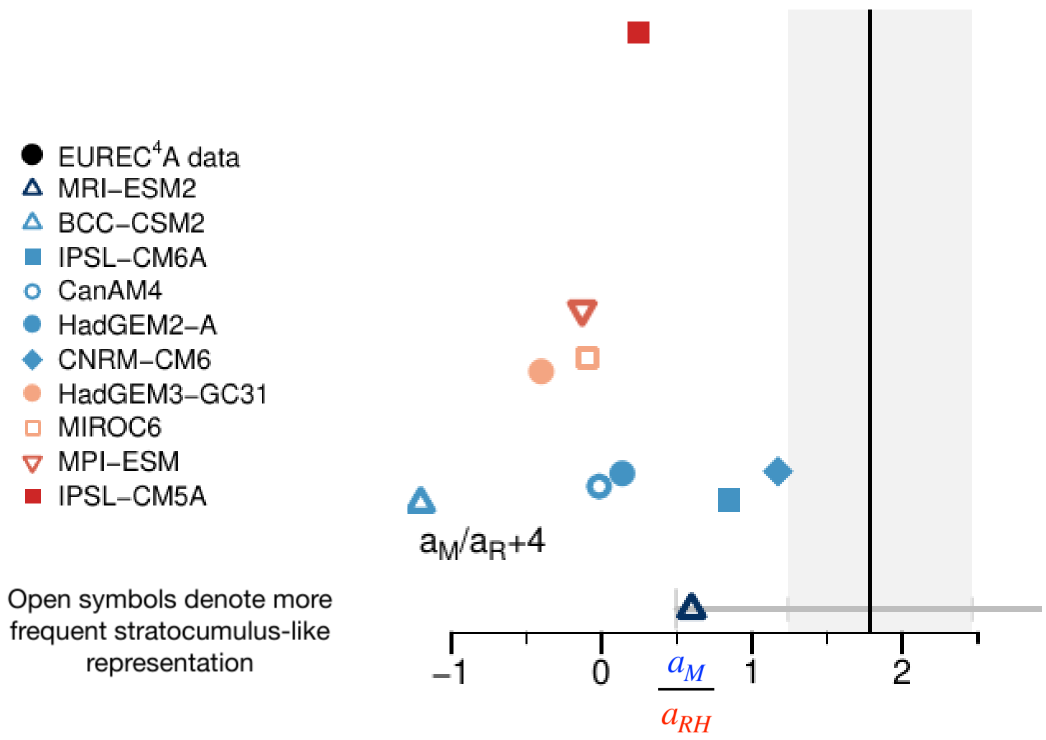
The dynamical control of clouds overwhelms
the thermodynamic control through humidity



Vogel et al. (in revision)



- High-frequency CFMIP model outputs (cfSites) from CMIP models near Barbados
- Mean and variability of M, RH, C differ a lot among models and between models and observations



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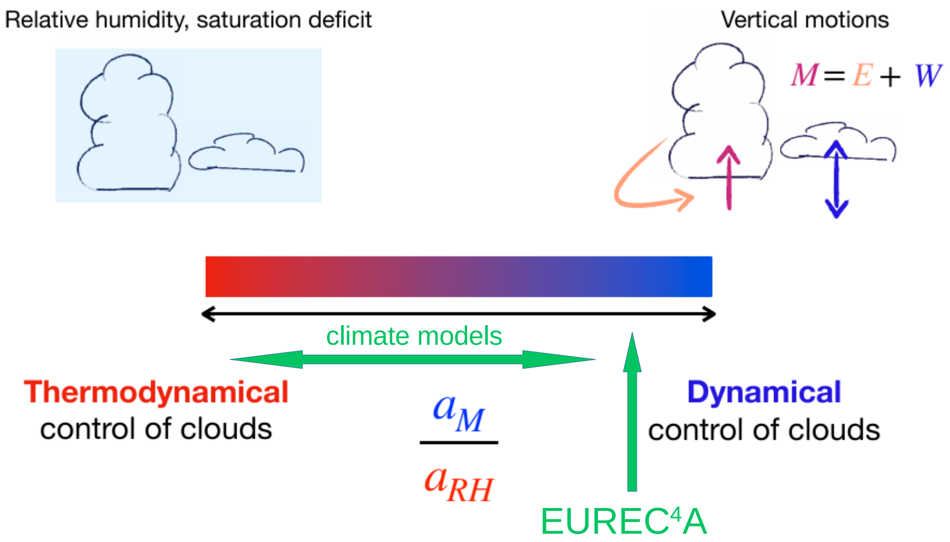

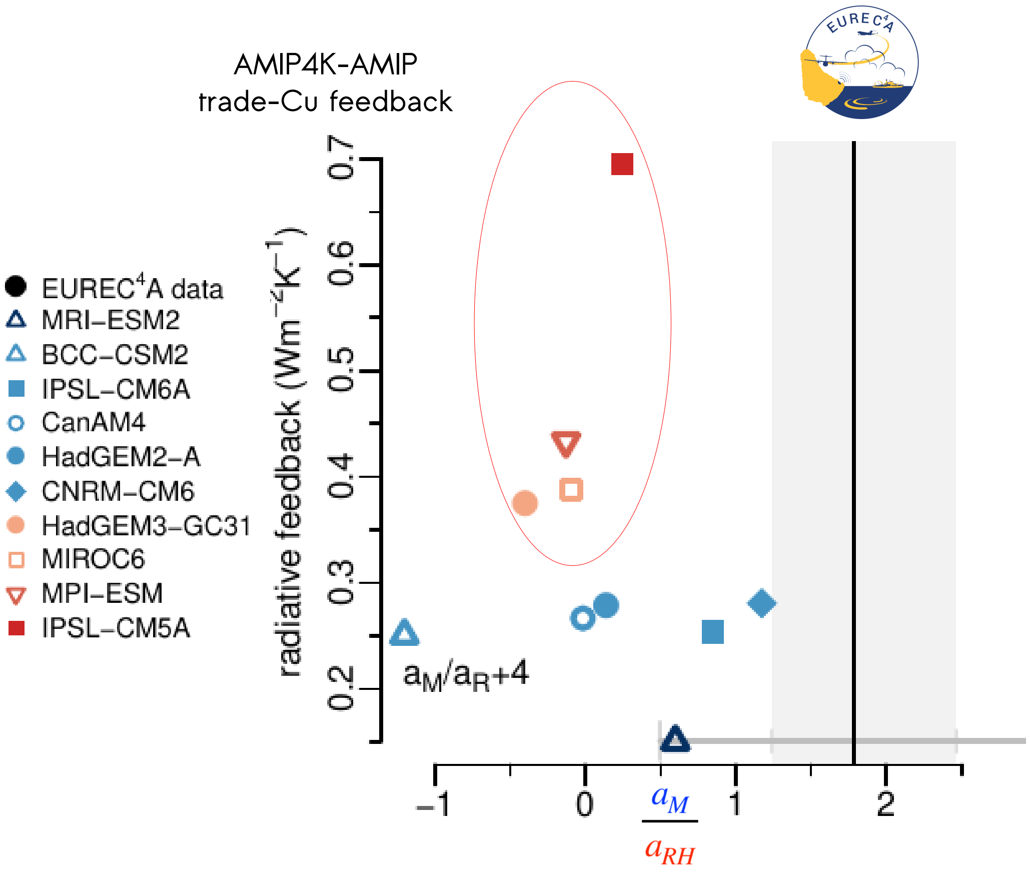

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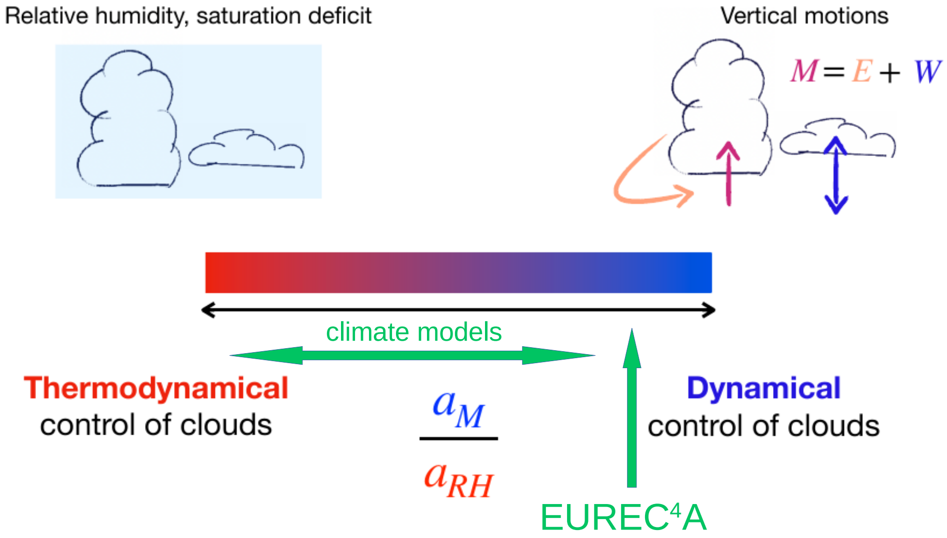

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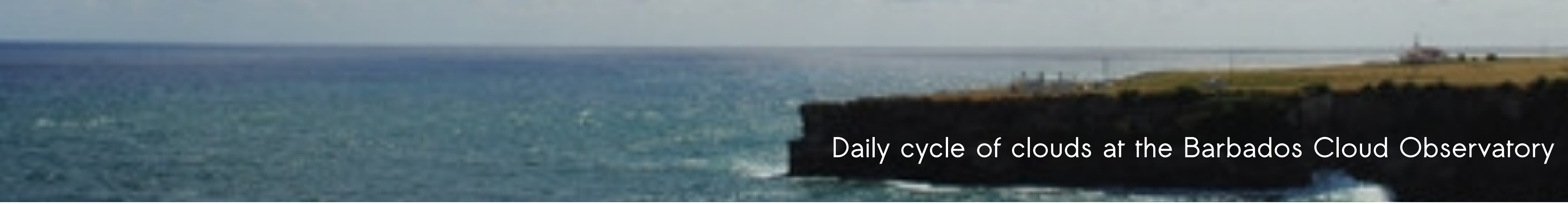
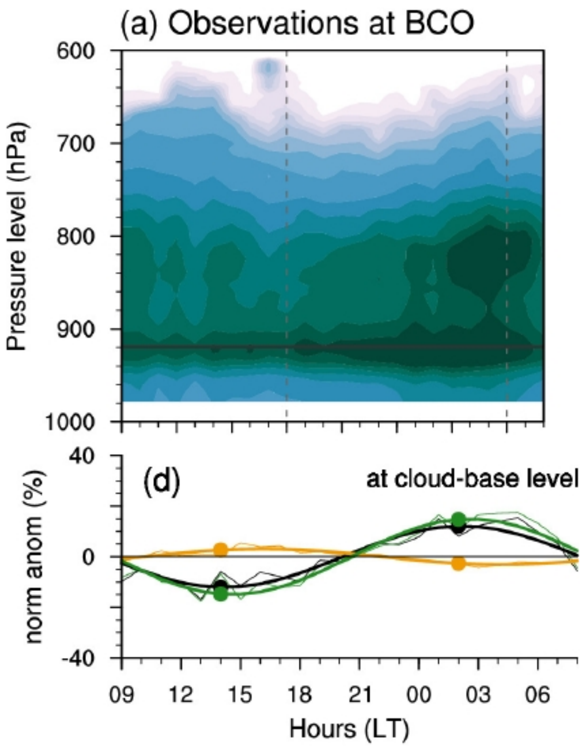
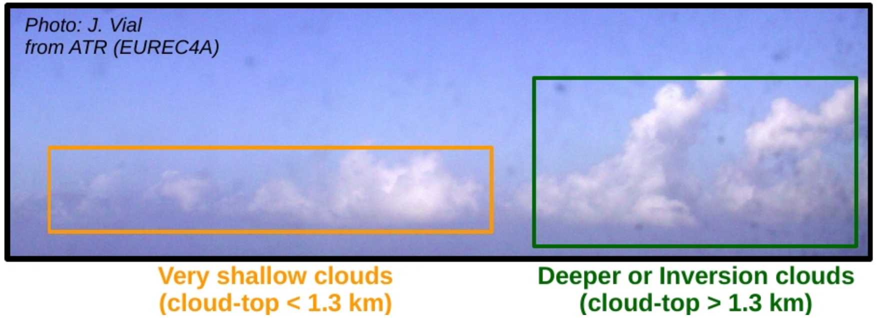
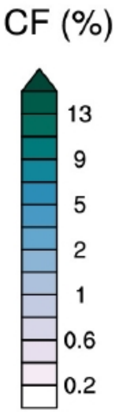
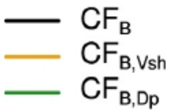


Daily cycle of clouds at the Barbados Cloud Observatory





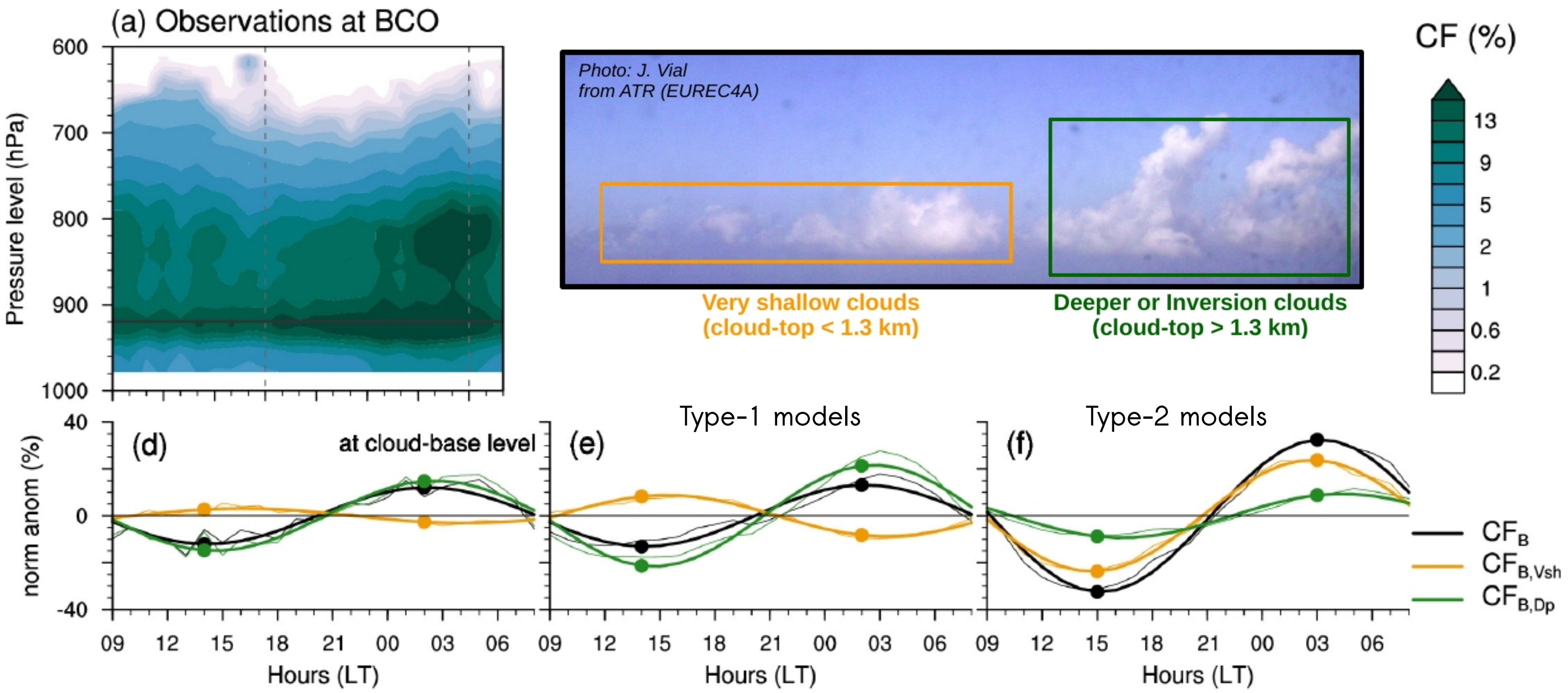




The daily cycle of cloudiness at cloud base results from a transition from very shallow clouds to deeper (but still shallow) convective clouds

Vial et al. (submitted)

Daily cycle of clouds at the Barbados Cloud Observatory



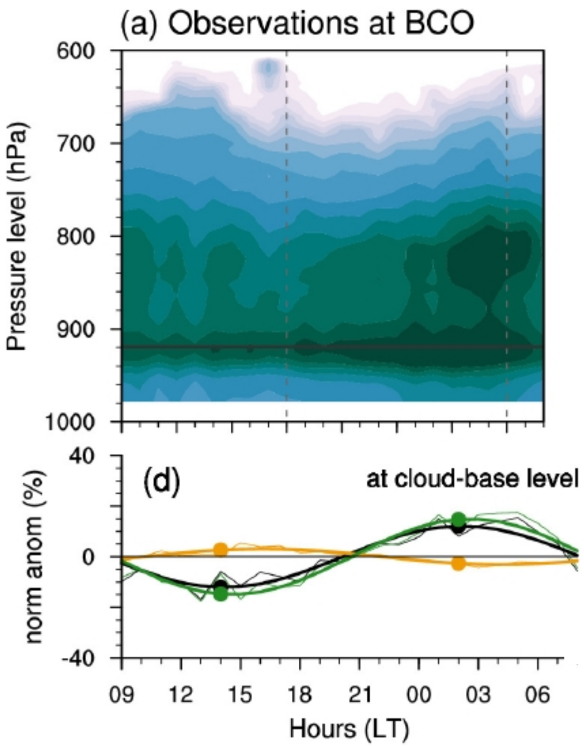
Some models reproduce this transition

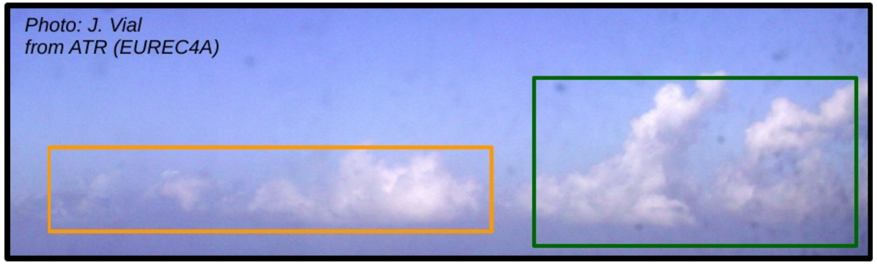
Others don't

Vial et al. (submitted)

Daily cycle of clouds at the Barbados Cloud Observatory

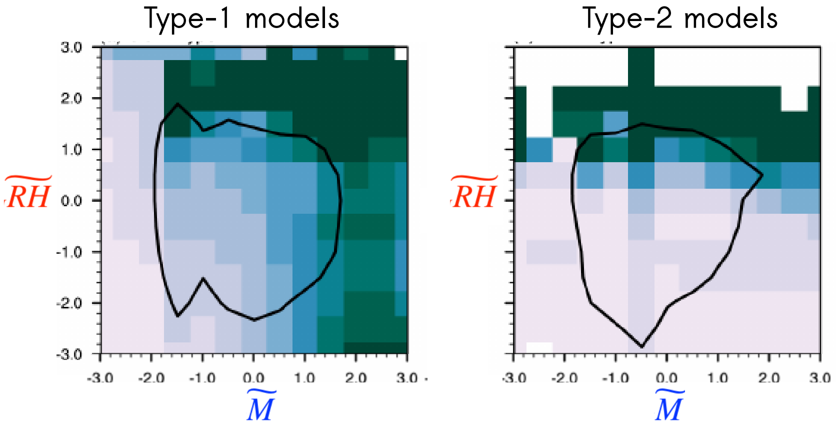
cfSite outputs





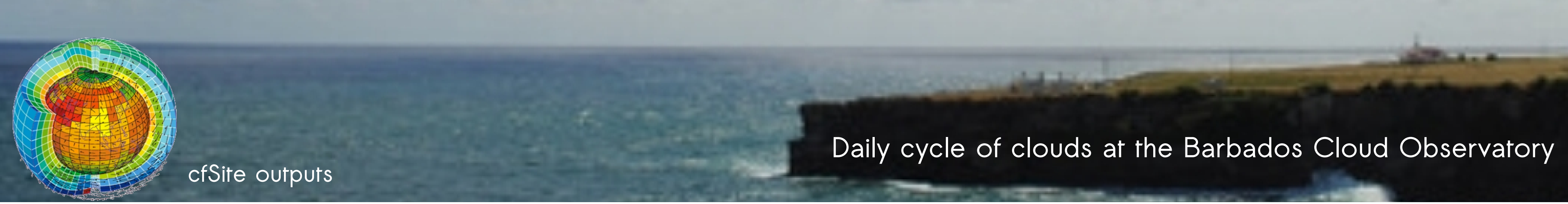
Very shallow clouds
(cloud-top < 1.3 km)

Deeper or Inversion clouds
(cloud-top > 1.3 km)



Variations of C
with M and RH

Vial et al. (submitted)



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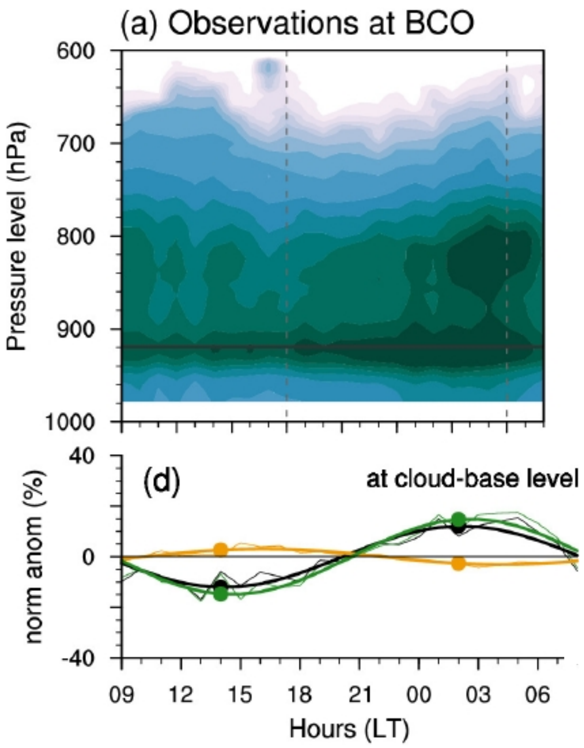
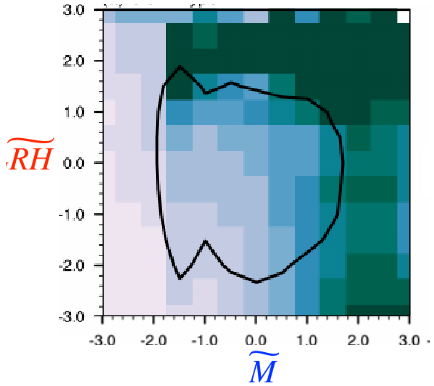


In models, the processes that control the daily cycle of cloudiness and the response of clouds to warming exhibit many similarities

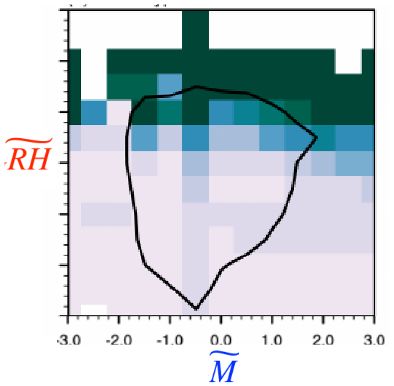
weaker radiative feedback

stronger radiative feedback

Type-1 models



Type-2 models



Models that represent the (dynamically driven) daily transition from shallow to deeper clouds :

- are more realistic
- predict a weaker sensitivity of cloudiness to RH changes
- predict a weaker feedback in climate change

Variations of C with M and RH

Vial et al. (submitted)

Take-home messages

- EUREC^{4}A observations do not support the mixing-dessication mechanism at work in a number of models.

- The daily cycle of cloudiness is an excellent testbed to understand and assess the processes underlying trade-cumulus feedbacks

- EUREC^{4}A and BCO observations suggest that trade-wind clouds are more dynamically controlled by convective and mesoscale motions than thermodynamically controlled by humidity variations

- Models that do not represent (or not sufficiently) the dynamical control of clouds :
  - exagerate the sensitivity of clouds to humidity, exagerate cloud variability, and tend to predict StCu instead of Cu
  - predict a stronger radiative feedback under climate change

- These observational, process-based constraints :
  → Connect the models' cloud feedback processes to the representation of physical processes
  → Render models with a strong shallow cumulus feedback implausible